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FRETTING FATIGUE CRACK NUCLEATION CRITERION FOR Ti-6Al-4V

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ABSTRACT

Fretting fatigue crack nucleation behavior in titanium alloy, Ti-6Al-4V was investigated by using two contact configurations: cylinder or flat with rounded edge pad on flat substrate. Both experiments and finite element analyses were conducted. A multiaxial fatigue parameter involving shear stress and normal stress on the critical plane was examined about its capability to predict the number of cycles to fretting fatigue crack initiation, crack initiation location and crack orientation angle along the contact surface. Also, the effects of two factors, crack nucleation process volume and coefficient of friction, on predictions were investigated.

INTRODUCTION

Fretting acts as a damage generator that leads to premature failure in components when subjected to cyclic loading relative to conventional fatigue. Majority of fretting fatigue life is spent in crack nucleation in the region where stress state is governed by contact conditions, while only a very small fraction of life is spent in crack propagation away from that region to a critical size. Therefore, a "crack nucleation approach" is a desirable technique to characterize fretting fatigue behavior. Further, this approach appears to be imperative since the tracking of cracks under fretting fatigue condition is a difficult task, because cracks are generally hidden under the mating bodies and current non-destructive methods are unable to monitor these small cracks, generally less than 100 μm. Further, contact region between two mating bodies, where crack nucleation occurs, is under a multi-axial state of stress even when subjected to a uniaxial fatigue load. Therefore, multiaxial fatigue models/criteria/parameters have been proposed in literature to characterize the fretting fatigue crack nucleation [1, 2].

However, majority of the previous studies have analyzed several parameters using only one contact geometry. Also, these parameters have been generally computed from stress/strain state at a critical location in the contact region. However, there exists a large stress/strain gradient over a volume/area in contact region which could have effects on crack nucleation behavior. Furthermore, stress/strain state depend heavily on the frictional behavior between mating bodies such as coefficient of friction. The present study provides the investigation on the effects of these two factors: 1) volume of material involved in crack initiation (referred to hereafter as process volume), and 2) coefficient of friction on fretting fatigue crack nucleation behavior of titanium alloy, Ti-6Al-4V using two contact configurations.

EXPERIMENTS

Two contact configurations were cylinder-on-flat and flat with rounded edges-on-flat geometries. The cylindrical pad had end radii of 50.8 mm, and flat pad configuration had a flat center section of 5.08 mm and edge radii of 5.08 mm. The flat specimen had gage section dimensions of 60 mm (length), 6.35mm (width) and 3.80 mm (thickness). Both specimens and pads were machined from Ti-6Al-4V forged plates which had a duplex microstructure consisting of 60% (volume) of primary-α (hcp) and 40% (volume) of transformed-β (α platelets in a β matrix - bcc) phases with a grain size of 10 ~ 15 μm. Fretting fatigue tests were conducted on a servo-hydraulic uniaxial test machine at ambient temperature, in a laboratory environment, and at a cyclic frequency of 200 Hz. This test setup applied cyclic stress, σ_{axial} and cyclic shear load, Q on the test specimen through fretting pad while holding the normal load, P constant on the pad. Details of experimental setup are provided in a previous study [3].

After fretting tests, all specimens were examined to document their failure mechanisms. It showed that failure occurred due to crack growth of a primary crack that initiated at the contact surface and near the trailing edge of contact along with few secondary cracks, which did not grow to a critical size. The experimentally observed primary crack orientations angles were either -45^0 or 45^0 with a variation of $\pm$ 15^0 from a perpendicular to the loading direction. The primary crack propagated at this orientation until it reached a certain depth (50 ~ 100 μm) where it turned perpendicular to the direction of the applied loading [4, 5].

CRACK NUCLEATION ANALYSIS

Similar to plain fatigue, crack initiation in fretting fatigue has been addressed by using critical plane based models where numbers of cycles to crack initiation are correlated with continuum field variables or some parameters dependent on the state of cyclic stress or strain or a combination of these. Therefore, stresses and strains were computed from finite element analysis of fretting fatigue experiments. Details of finite element analysis are available in a previous study [6]. Four parameters: Smith-Watson-Topper Parameter (SWT), Shear Stress Range Parameter (SSR), Findley Parameter (FP), and Modified Shear Stress Range Parameter (MSSR) were examined in detail [5]. SWT parameter is based on normal stress at the critical plane, shear stress range parameter is based on shear stress range at the critical plane, and Findley and Modified Shear Stress Range (MSSR) parameter are based on some combinations of shear and normal stresses on the critical plane. In this previous study, these critical plane parameters were calculated at all points in the contact region, for all orientations ranging from $-90° \leq \theta \leq 90°$ from a perpendicular to the contact surface, using the computed stresses and strains from finite element analysis of fretting fatigue experiments. From these calculations, location and orientation of crack initiation were determined at the point and the corresponding orientation of the critical plane, where the maximum value of the parameter occurred. Also, these parameters were correlated with the crack nucleation life data. If parameter is appropriate, then these predictions and correlation of fatigue life data should be independent of pad/contact geometry, since variations in these geometries provide different degrees of multiaxiality in the stress state in contact region. This investigation

showed that the MSSR parameter was capable to satisfy these all requirements [5]. The MSSR parameter is expressed as follows:

$$MSSR = A.\Delta\tau^{B}_{crit} + C.\sigma^{D}_{max} \quad (1)$$

First the shear stress range ($\Delta\tau = \tau_{max} - \tau_{min}$) was computed, from the stress state obtained from finite element analysis, at all points along all planes in the contact region which provided a critical plane where this range had the maximum value. Here τ_{max} and τ_{min} are shear stresses due to the maximum and minimum applied fatigue loads, respectively. Then, shear stress ratio effect on the critical plane was accounted by incorporating a technique proposed by Walker [7] which is expressed as:

$$\Delta\tau_{crit} = \tau_{max}(1-R_{\tau})^{m} \quad (2)$$

where τ_{max} is the maximum shear stress on the critical plane, R_{τ} is shear stress ratio on the critical plane, and m is a fitting parameter, which was determined to be 0.45 from the plain fatigue data [2]. The second term, σ_{max} in equation 2 is the maximum normal stress acting on the critical plane defined by the maximum shear stress range. The values of A, B, C, and D in equation 2 were determined empirically to provide a good fit to all experimental data, and these are A = 0.75, B = 0.5, C = 0.75 and D = 0.5 [5]. Figure 1 shows the measured fretting fatigue life data as a function of MSSR parameter, which show a negligible or very little dependence on pad geometry. Furthermore, MSSR parameter satisfactorily predicted angle of crack orientation and crack location, which were in agreement with their experimental counterparts [5].

As mentioned earlier, the MSSR (shown in Figure 1) was calculated from stress state at a point in the contact region. However, stress/strain state has a sharp gradient over a small volume/area in the contact region. Therefore, crack nucleation may depend on some volume of material, i.e. fretting fatigue process volume (FFPV), and not just on stress/strain state at a critical point. Therefore, the parameter was computed over a FFPV having a radius, R_{FFPV} ranging from 0 to 100 μm (i.e. from a point to about five to six times of the grain size in titanium alloy tested). The details of this volume averaging method are given in Reference 8. It can be seen from Figure 2 that angles of crack initiation predicted by the parameter are about $\pm 45^{o}$ before or after incorporating process volume averaging method in the computation for both contact geometries, and it is agreement with the experiments. In other words, there is not much variation in the predicted crack initiation angle, when parameters are calculated over R_{FFPV} from 0 to 100 μm. Figure 3 shows fatigue life diagram, for both contact geometries, when the calculations were carried with process volume having $R_{FFPV} = 0$ and 50 μm representing a point, and material of the order of three times the grain size, respectively. It can be seen from Figure 3 that the parameter depends on the process zone size, i.e. it is inversely proportional to the value of R_{FFPV}. This is expected due to the high stress gradient in the contact zone.

Next, effects of coefficient of friction (μ) on the calculation of parameter were investigated. For this purpose, two values of μ, 0.5 and 0.8, were considered. Coefficient of friction measured from experiments was 0.5 that stabilized after specimens were subjected to about

5,000 cycles. So, the other value of $\mu = 0.8$ was used to represent any variation or uncertainty in its measurement, as well as a worst-case scenario. Figure 4 shows fatigue life diagram for two values of μ for $R_{FFPV} = 0$ μm representing the point calculation. This clearly shows that increase in coefficient of friction increases the value of parameter in the case of cylindrical pad, but a little variation in the value of parameter due to the variation of coefficient of friction in the case of flat pad. This was due to the fact that the peak value of parameter for flat pad was not much affected by the change in coefficient of friction but affected the parameter value along the whole contact region. On the other hand for cylindrical pad, the major effect was concentrated mainly at the peak value of parameter. This phenomenon is just opposite of that observed in the case of process volume, i.e. value of parameter decreases with the increase in size of process volume, and these process variables are thus competing against each other in the case of cylinder-on-flat contact configuration. Furthermore, there is a consistent shift in fatigue life relationship for a given process volume size independent of the contact geometry.

SUMMARY

It appears that fretting fatigue crack nucleation behavior (cycles to fretting fatigue crack initiation, crack initiation location, and crack orientation) can be characterized by using a critical plane parameter, MSSR involving both normal and shear stresses (i.e. combination of tensile and shear cracking mode). Predicted crack orientation did not change when the process volume and coefficient of friction was varied. Further, the predicted fatigue life was affected by the size of process volume and the value of coefficient of friction but the latter had a minimal affect in the case of flat with rounded edge contact geometry.

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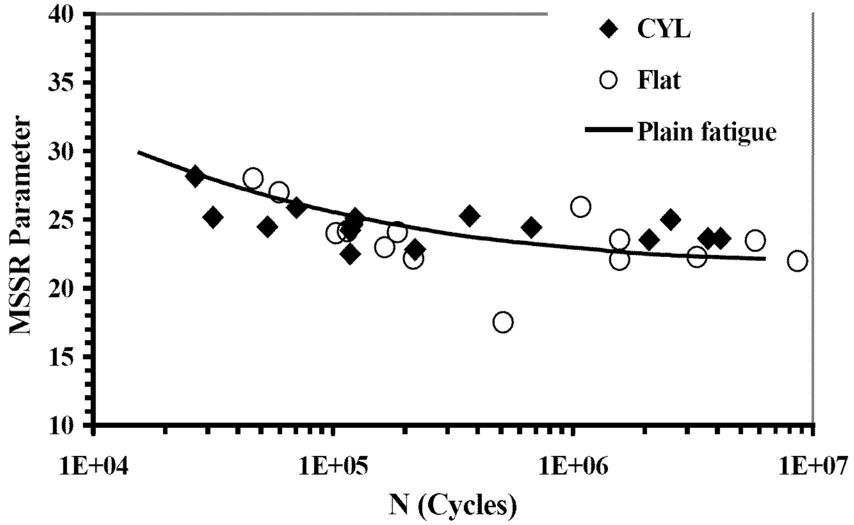

Figure 1. MSSR versus cycles to failure.

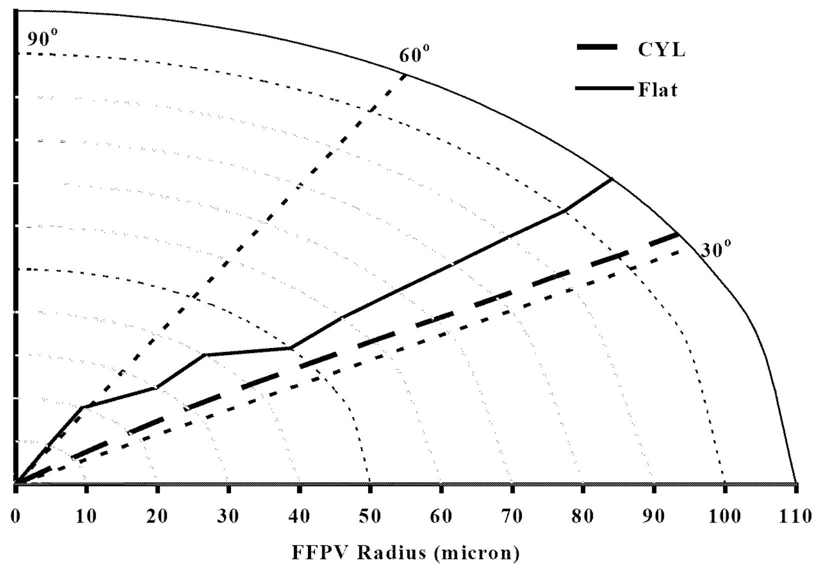

Figure 2. Crack Orientation as function of process volume size.

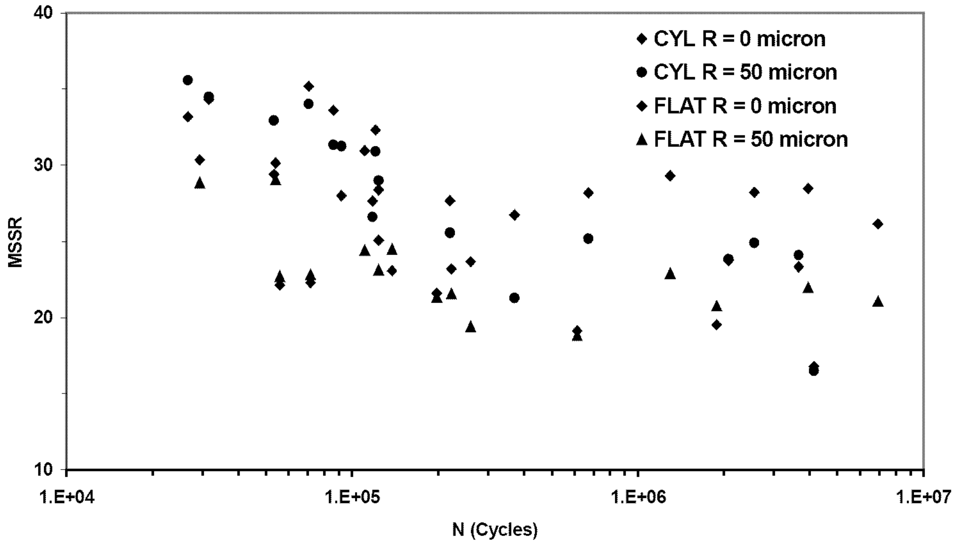

Figure 3. Effect of process volume size.

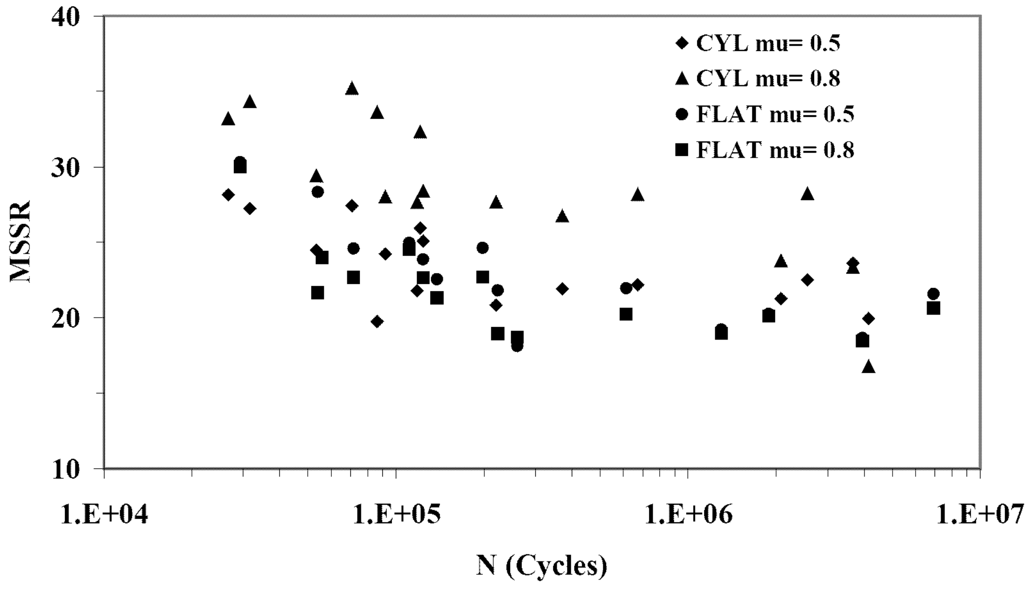

Figure 4. Effect of coefficient of friction